XVII. Dhofar 019 (ver. 2003)

Basalt

1056 grams

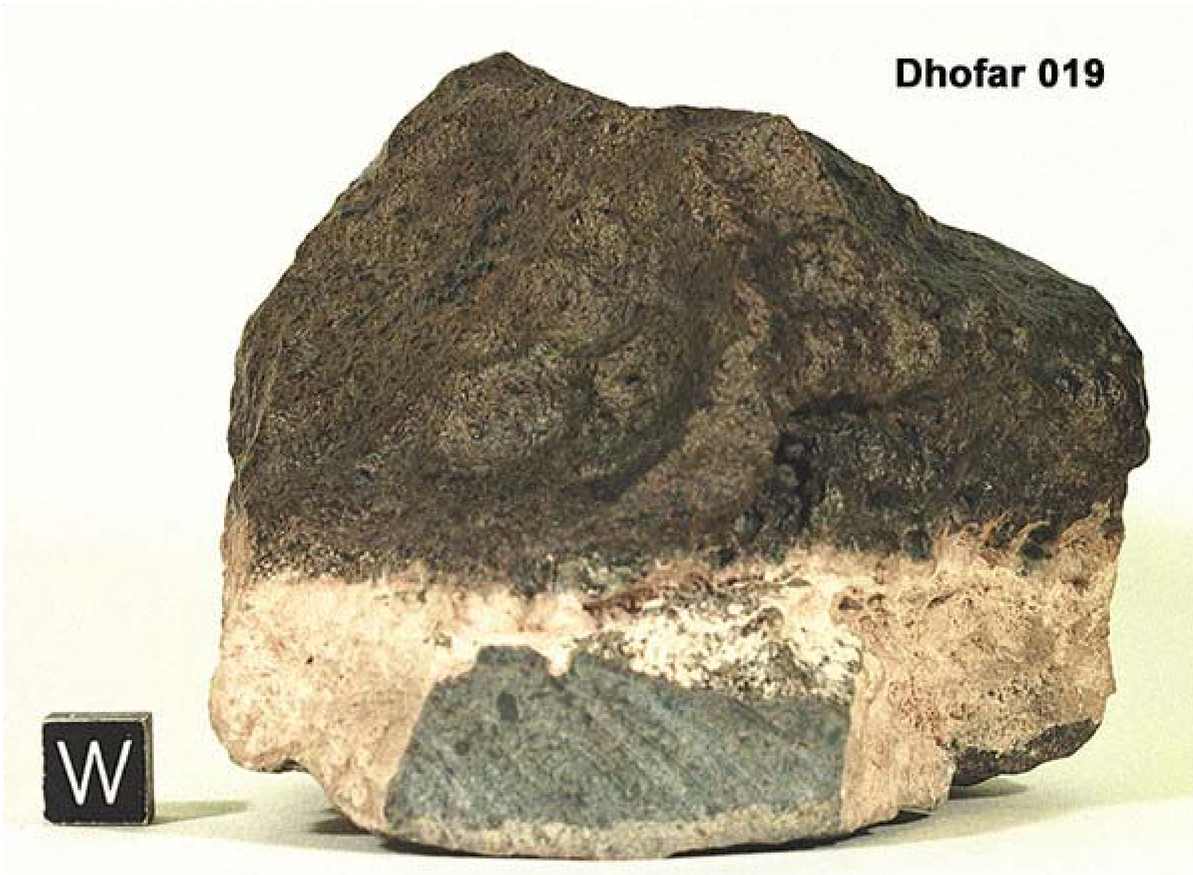

***Figure XVII-1**: Photograph of Dhofar 019 showing calichi and saw cut (figure kindly provided by Larry Taylor).*

Introduction

Dhofar 019 was found in Oman in January 2000 (Grossman 2000). It weighs 1,056 grams and has no fusion crust. Figure XVII-1 shows the main mass and the location of the saw cut providing the material studied. Cahill *et al.* (2002) find that Dho 019 is heterogeneous with some apparent layering.

Petrography

Dhofar 019 is described as a basaltic/doleritic rock consisting of subhedral grains (0.2-0.5 mm) of pyroxene, feldspar converted to maskelynite, and olivine (Taylor *et al.* 2000, 2002). Accessary phases are silca, K-rich feldspar, whitlockite, chlorapatite, chromite, ilemnite, titanomagnetite, magnetite, and pyrrhotite; secondary phases are calcite, gypsum, smectite, celestite, and Fe hydroxide. Melt inclusions are widely distributed throughout olivine grains and present in a few chromite grains (Cahill *et al.* 2002).

Mikouchi and Miyamoto (2001) observe that Dho 019 shows a close mineralogical relationship to EETA 79001, Dar al Gani 476 and Sayh al Uhaymir 005.

Shock features include fracturing and mosaicism, maskelynite, and rare impact-melt pockets. Planer fractures in olivine occur as two, rarely three, sets of straight, parallel cracks 10-60 microns apart. Pyroxene grains have abundant polysynthetic mechanical twins, about 1-4 microns in thickness. Badjukov e*t al.* (2001) estimate a shock pressure in the range of 30-35 GPa.

The bottom portion of the meteorite was apparently buried in caliche soil (also see nice picture of main mass in Taylor *et al.* 2002). Calcite is present mainly as veins cross-cutting the meteorite.

Hydrous alteration phases: Taylor *et al*. (2002) report two types of "smectite" in Dho 019, giving rough analyses.

Modal Mineralogy

	Taylor *et al.* (2000)	Mikouchi and Miyamoto (2001)	Taylor *et al.* (2002)
Olivine	9	13.7	10.1
Pyroxene	64	64.6	61.4
Plagioclase	25	19.5	26.1
Phosphates		1	
Opaques		1.2	1.8

Mineral Chemistry

Olivine: Lentz and McSween (2001), Mikouchi and Miyamoto (2001) and Taylor *et al.* (2002) have studied the olivine compositions (Fo_{73-25}). Rare olivine megacrysts (>1.5 mm) have Mg-rich cores (Fo_{73}), but most olivine grains are small (<200 microns) and relatively Fe-rich. The relative high CaO content of olivine (0.35%) is characteristic of extrusive rocks. Shearer *et al*. (2001) have determined the Ni (170-260 ppm) and Co (220-330 ppm) in olivine grains and find that they were lower than that in olivine from other Martian meteorites.

Pyroxene: Pigeonite $En_{40-70}Wo_{9-15}$ is commonly rimmed with augite $En_{40-50}Wo_{30-40}$ (figure XVII-2). No orthopyoxene is found, although it is predicted to have been an early forming mineral (Taylor *et al.* 2002). Al-rich augites are found in melt inclusions.

Feldspar: Plagioclase An_{36-68} has been wholly transformed to maskelynite (Badjukov *et al.* 2001).

Phosphates: Merrillite (whitlockite) is typically homogeneous $Ca_{8.9}(Mg,Fe)_{1.1}Na_{0.3}(PO_4)_7$ (Mikoucki and Miyamoto 2001). Taylor *et al.* (2002) also report analyses of merrillite and of chloro-apatite.

Oxides: Ilmenite and chromite analyses are given in Taylor *et al.* (2002). Chromite cores are overgrown by Cr-ulvöspinel rims.

Sulfide: Taylor *et al.* (2002) determine that the (Fe+Ni+Co)/S ratio of sulfide grains in Dho 019 is ~0.87, corresponding to the formula Fe_7S_8 of pyrrhotite.

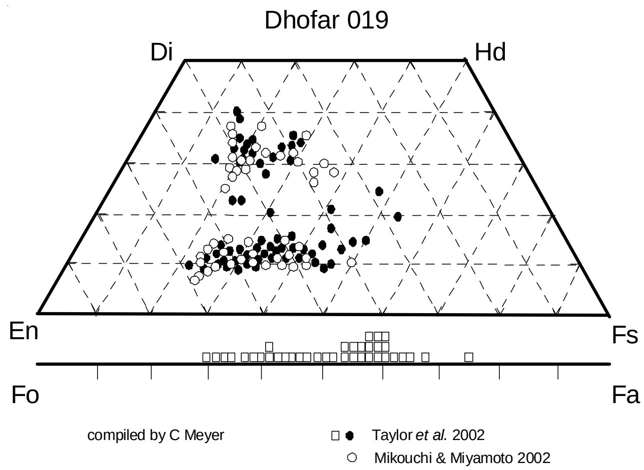

Figure XVII-2: Pyroxene and olivine composition diagram for Dhofar 019 (data replotted from Taylor et al. 2002 and Mikouchi and Miyamoto 2002).

Whole-rock Composition

The chemical composition of Dhofar 019 was reported by Taylor *et al*. (2000, 2002) (Table XVII-1). Neal *et al*. (2001) determined the trace element contents, including the PGEs. Dho 019 is interpreted as a "melt product derived from a source already depleted in the incompatible elements and the PGEs" (Neal *et al.* 2001). In addition to being "depleted" in LREE (figure XVIII-3), Dho 019 is also found to be "depleted" in Rb, Nb, Ta and Th (figure XVII-4).

High CaO, SO_3, CO_2 and H_2O contents point to a significant terrestrial enrichment in secondary Ca-carbonates, sulfates and clay minerals in the split analyzed. One split had a positive Ce anomaly (figure XVII-3), high Sr and U (figure XVIII-4) indicating terrestrial weathering.

Radiogenic Isotopes

Borg *et al*. (2001) determined a Sm-Nd age of 575 ± 7 Ma for Dhofar 019 (figure XVII-5). The Rb-Sr systematics were slightly disturbed by terrestrial weathering, but a consistent Rb/Sr age of 525 ± 56 Ma was determined (figure XVII-6). Note that this age is older than that of the other basaltic shergottites (180-475 My).

Cosmogenic Isotopes and Exposure Ages

Shukolyukov *et al*. (2000) determined exposure ages of 18.1 Ma from ^{21}Ne and 21.4 Ma from ^{38}Ar, which are the longest so far, for Martian meteorites. Park *et al*. (2001) report a ^{21}Ne exposure age of 12 Ma. Other shergottites have exposure ages in the range of 0.6 to 5 Ma.

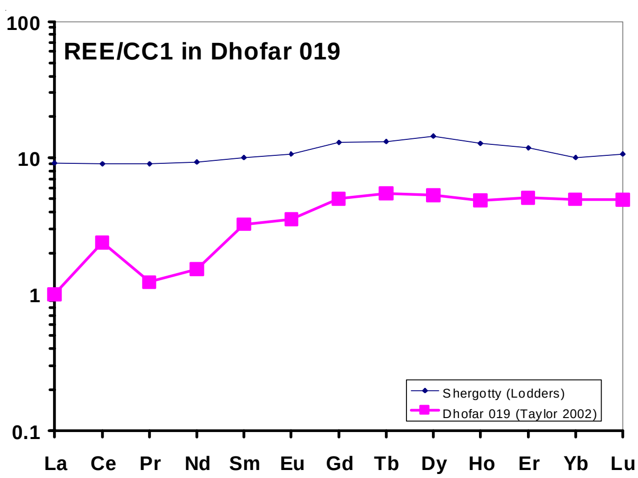

***Figure XVII-3**: Rare earth element diagram for Dhofar 019 compared with Shergotty (data from Taylor et al. 2002 and Lodders 2000).*

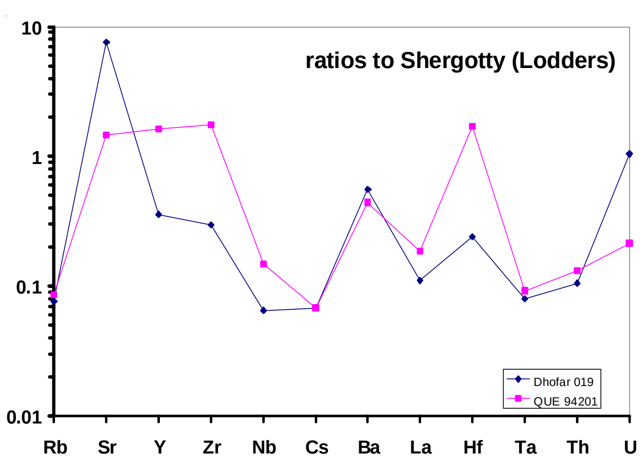

***Figure XVII-4**: Trace element contents of Dhofar 019 and QUE 94201 divided by composition of Shergotty (for reference).*

Other Isotopes

Taylor *et al*. (2002) reported the oxygen isotopic composition as $\delta^{17}O = 2.99‰$ and $\delta^{18}O = 5.4‰$ with $\Delta^{17}O = 0.18‰$. Of all the Martian meteorites, Dho 019 is the most enriched in ^{17}O and ^{18}O.

Terrestrial Weathering

There can be no doubt that this meteorite was badly weathered in the desert in Oman (see figure XVII-1). It has calcite, gypsum and a positive Ce anomaly (figure XVII-3). Nanometer-ovoids found within the caliche on the outside of Dho 019 are similar to those found inside (Folk *et al.* 2001).

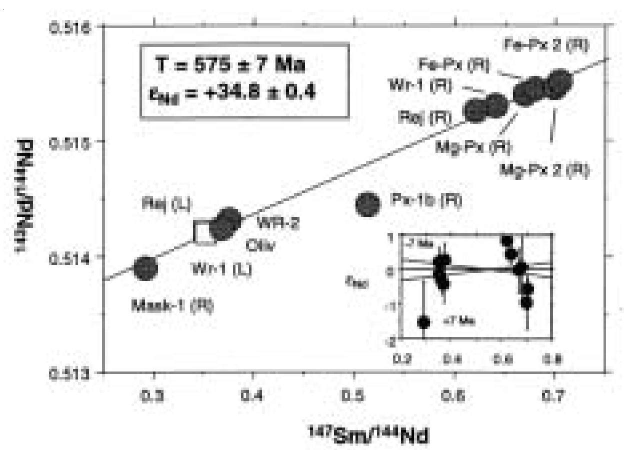

***Figure XVII-5**: Sm-Nd internal mineral isochron for Dhofar 019 (from Borg et al. 2001, **LPSC XXXII**).*

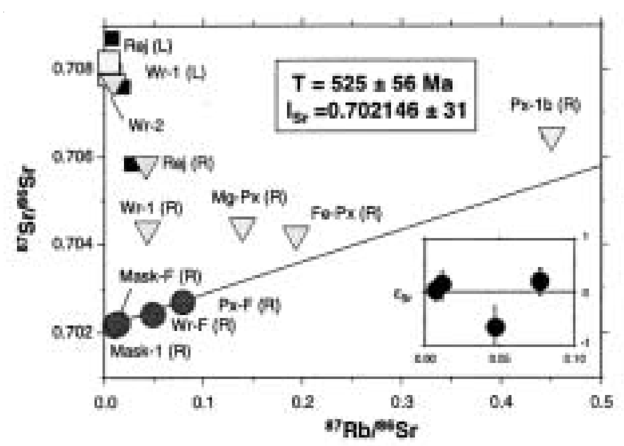

***Figure XVII-6**: Rb-Sr internal isochron for mineral separates of Dhofar 019 (from Borg et al. 2001, **LPSC XXXII**).*

Extra-terrestrial Weathering ??

Taylor *et al.* (2000) report "numerous zoned smectite-calcite-gypsum "orangettes", morphologically similar to those in ALH84001". It is reported that these secondary phases are located mainly at maskelynite borders with pyroxenes as "mineralogically-zoned grains, which appear to replace maskelynite" (Taylor *et al.* 2002). Taylor *et al.* (2002) illustrate one round patch of "smectite" with intersecting microfault that would seem to suggest that some alteration must be from Mars! *(note: This is very hard to distinguish in this rock, because of evidence for extensive terrestrial weathering)*

Processing

The Vernadsky Institute, Moscow, has specimens of 113 grams, 4 grams, and 2 grams, and two thin sections; but the main mass remains with the anonymous finder (Larry Taylor?).

Table XVII-1: Chemical composition Dhofar 019.

reference	Taylor 2000	Neal 2001	Neal 2001	Taylor 2002		Taylor 2002		Taylor 2002
weight				1 gram		115 mg		calc.
SiO2	49.2			45.52	(b)			48.4
TiO2	0.7	0.49		0.594	(b)	0.49	(a)	0.63
Al2O3	6.4	6.65		6.72	(b)	6.65	(a)	7.01
FeO	18.4	19.9		17.93	(b)	19.9	(a)	19.1
MnO	0.49	0.48		0.461	(b)	0.48	(a)	0.49
CaO	7.28	9.42		9.27	(b)	9.42	(a)	7.08
MgO	14.6	14.6		14.61	(b)	14.6	(a)	15.5
Na2O	0.92	0.89		0.677	(d)	0.89	(a)	0.72
K2O	0.1			0.053	(d)			0.05
P2O5		0.4		0.401	(b)	0.4	(a)	0.41
sum				96.236				100
Li ppm		2.88	2.84			2.86	(a)	
Be		0.04	0.02			0.03	(a)	
Sc		30.2	32.2	33.8	(c)	31.2	(a)	
V		168.5	181.6			175.1	(a)	
Cr		3164	3670	3900	(c)	3417	(a)	
Co		42.9	46.1	39.1	(c)	44.5	(a)	
Ni		63.8	66.8	100	(c)	65.3	(a)	
Cu		9.4	9.68			9.54	(a)	
Zn		61.9	62.1			62	(a)	
Ga		9.81	10.6			10.21	(a)	
Se				0.32	(c)			
Br				0.19	(c)			
Rb		0.52	0.46			0.49	(a)	
Sr		*361*	*364*	285	(c)	*363*	(a)	
Y		6.81	6.75			6.78	(a)	
Zr		15.2	19.6	50	(c)	17.4	(a)	
Nb		0.29	0.31			0.3	(a)	
Mo		0.42	0.63			0.52	(a)	
Sb ppb		20	10	40	(c)			
Cs ppm		0.02	0.03	0.32	(c)	0.03	(a)	
Ba		20	18.8	70	(c)	19.4	(a)	
La	0.2	0.24	0.24	0.3	(c)	0.24	(a)	
Ce	0.68	1.48	1.42	1.1	(c)	1.45	(a)	
Pr		0.1	0.11			0.11	(a)	
Nd		0.65	0.73	1.6	(c)	0.69	(a)	
Sm	0.44	0.51	0.45	0.82	(c)	0.48	(a)	
Eu	0.081	0.17	0.23	0.14	(c)	0.2	(a)	
Gd		0.96	1.01			0.99	(a)	
Tb		0.2	0.2	0.22	(c)	0.2	(a)	
Dy		1.32	1.28			1.3	(a)	
Ho		0.27	0.27			0.27	(a)	
Er		0.86	0.75			0.81	(a)	
Tm		0.11	0.12			0.12	(a)	
Yb	1.29	0.85	0.76	0.74	(c)	0.81	(a)	
Lu	0.26	0.13	0.11	0.13	(c)	0.12	(a)	
Hf		0.46	0.5	0.7	(c)	0.48	(a)	
Ta		0.02	0.02	0.1	(c)	0.02	(a)	
W ppb		10	40			30	(a)	
Ir ppb		0.127		<9		0.127	(a)	
Ru ppb		0.354				0.354	(a)	
Rh ppb		0.295				0.295	(a)	
Pt ppb		3.969				3.969	(a)	
Pd ppb		1.718				1.718	(a)	
Th ppm		0.04	0.03			0.04	(a)	
U ppm		0.1	0.12			0.11	(a)	

technique: a) ICP-MS, b) ICP and XRF, c) INAA, d) AA